EXPERIMENTAL STUDIES ON THE THERMAL BEHAVIOUR OF SILVER (Ag) ORNAMENTED GRAPHENE OXIDE (GO) HYBRID NANOFLUIDS IN HEAT EXCHANGING SYSTEMS

A SYNOPSIS

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1. INTRODUCTION

Over the past decade, global energy demand has grown significantly due to advancements in technology, population growth, and industrial development. Projections indicate a 48% increase in global energy demand over the next 20 years due to the growing world population [1]. Additionally, energy-intensive industries like manufacturing, power, transportation, and construction have flourished as countries strive for economic development and competitiveness, putting further strain on energy resources. Addressing the complexities of global energy demand requires comprehensive strategies that balance energy efficiency and conservation measures in both industrial and residential sectors. One effective approach is to optimize heat transfer in heat exchanging systems by using high-performance nano-sized materials in the equipment and working fluids. This can prevent unnecessary heat loss and enhance power production and efficiency, making it a promising option [2]. By adopting these effective heat transfer optimization strategies, would contribute more sustainable and secure energy future for generations to come. Despite researchers studying heat exchanging systems for decades, such as double pipe heat exchangers (DPHX) and heat pipes (HP), using innovative methods like introducing different mono or hybrid nanofluids, there is still room for improvement and optimization. With advancements in nanotechnology, there's a growing interest in finding better hybrid materials, methods, and strategies to improve thermal performance in heat exchanging systems. The choice of hybrid nanoparticles for heat transfer applications depends on their thermal properties, stability, cost, and synthesis method. Among carbon, metal, and metal oxide nanoparticles, graphene oxide (GO) and silver (Ag) nanoparticles stand out for their unique properties in thermal augmentation research. From the literatures observed the nanoparticles of GO as a carbon structure and Ag as metal nanoparticles are appealing for their enhanced thermal properties in various thermal applications when used separately. According to the existing literatures [3], GO nanoparticles possess unique properties, such as hexagonal carbon structures, high surface-to-volume ratio, long stability duration, high thermal conductivity, controllable porosity and band gap, and better catalytic properties like electron acceptors and high elasticity, making them suitable for thermal management applications. Similarly, Ag nanoparticles are useful in various thermal applications due to their small size, high surface area, and unique electron transport properties.

These attractive properties of both GO and Ag make them a promising candidate for creating hybrid nanofluids, which were studied in this research by preparing different molar doping of Ag on GO nanoparticles to observe its fascinating changes in thermal properties and application of the prepared Ag ornamented GO nanofluids in DPHX and HP to evaluate its thermal performances.

2. LITERATURE REVIEW

In the field of heat transfer, enhancing the thermal performance of heat exchanging systems has been a long-standing focus for researchers. Traditional heat transfer fluids, such as water, ethylene glycol, and oil, have limitations in terms of heat transfer efficiency, prompting the search for innovative solutions Vallejo et al. [4]. To address this challenge, researchers have explored the incorporation of nanomaterials with high thermo-physical properties into these fluids. Various types of nanofluids, including metals, metal oxides, and carbon-based nanofluids, have been developed in both mono and hybrid forms. These nanofluids are engineered to possess high thermal properties, thus enhancing the thermal transport in compact cooling systems. The investigation of nanofluids in heat transfer applications necessitates attention to three key factors: preparation strategy, stability, and thermophysical properties. The two-step approach for preparing nanofluids has proven significant, overcoming limitations in mass production compared to the single-step method. Heat exchanging systems often require larger volumes of nanofluids, making the two-step approach more favourable.

In the last decenary, graphene oxide (GO) has gained significant attention within the realm of carbon allotropes due to its exceptional properties, particularly in the field of thermal investigations Mbambo et al. [5]. Researchers have explored GO's potential in enhancing heat transfer performance by employing the two-step approach for nanofluid preparation. GO nanoparticles are synthesized chemically from graphite using a Hummers approach which offers several advantages such as simplicity in wide-scale synthesis, hydrophilic properties, and higher thermal conductivity as well as superior surface chemistry for retaining doping species Majumder and Gangopadhyay [3]. For instance, in the applications of DPHX, Karabulut et al. [6] applied GO/distilled water nanofluids in a copper pipe heat exchanger with turbulent flow under constant heat flux, achieving a 48% increase in maximum heat transfer coefficient at 0.02 vol% and 1.5 l/min flow rate (Re 5032). Similarly, Ranjbarzadeh et al. [7] utilized GO nanoparticles at 0-0.15

vol.% to enhance heat exchanger efficiency, thermal conductivity, and convective heat transfer in industrial cooling systems, resulting in a 34.7% increase in convective heat transfer coefficient and 9.64% increase in friction factor over the base fluid. In alignment with heat pipe, Kim and Bang [8] conducted research on cylindrical screen mesh wick heat pipes using 0.01 vol.% and 0.03 vol.% graphene oxide (GO) mixed with water as the working fluid. Their findings revealed a substantial 25% decrease in the thermal resistance of the evaporator section, attributed to the enhanced capillary action facilitated by the GO nanoparticle coating. GO has also been widely explored in combination with various metal nanoparticles dopants to create hybrid nanofluids with enhanced thermophysical, optical, and chemical properties compared to base fluids. For instance, Jodh Singh et al. observed a significant 30% improvement in the thermal conductivity of GO-CuO/DW nanofluids at 0.3 wt.% and 60℃. Similarly, Dan Li et al. [9] prepared an ethylene glycol-based GO-Ag hybrid nanofluid and noted a 22% increase in thermal conductivity at 45°C with a mass fraction of 0.3 wt.% in the temperature and mass fraction range of 20–45°C and 0.1, 0.2, and 0.3 wt.%, respectively. Furthermore, Kumar et al. [10] conducted research on the heat transfer performance of GO and rGO-CuO nanofluids in a laminar regime within a heat exchanger tube and found a substantial 53.33% increase in the heat transfer coefficient using rGO-CuO nanofluid at 0.05 wt.% compared to DI water. Among these dopants, Ag nanoparticles over GO have garnered significant attention due to their exceptional thermophysical and reactive properties, as well as their potential as a superior Surface Enhanced Raman Scattering (SERS) framework, offering novel prospects across various disciplines Kumari et al. [11]. Researchers have explored diverse methods to create Ag-decorated GO hybrid nanoparticles, notably, the chemical reduction method has stood out for its higher production rate and cost-effectiveness.

In a different doping perspective, Hui et al. [12] characterized different molar concentrations (0.1M, 0.2M, 0.6M) of Ag doped over GO through in situ ultrasonication using ascorbic acid as a reducing agent. The ultrasonication time and silver nitrate amount influenced Ag nanoparticle dimensions across all concentrations. Additionally, Lozano-Steinmetz et al. [13] investigated the thermal properties of different concentrations of Ag (0.01 M, 0.1 M, and 1 M) doped into reduced graphene oxide (rGO). This study highlighted the significant enhancement of nanofluid properties with the use of 0.1M Ag concentration, suggesting its potential application in heat transfer systems. Despite these advancements, a research gap still exists in identifying the optimum molar doping of

species, both experimentally and mathematically, in heat exchanging systems like DPHX and HP. Since, the majority of the existing studies primarily focus on changes in weight and volume concentrations of prepared hybrid nanoparticles.

Building upon the foundations laid by these scientific reports and knowledge, this study endeavours to investigate the heat transfer performance in an annulus of the DPHX and heat pipe by utilizing varied lower molar (0.03 M, 0.06 M & 0.09 M) Ag ornamented GO hybrid nanofluids at 0.05 wt.% with varying mass flow rates. The research meticulously examines materials characterization, stability, thermo-physical properties, and thermal performance to contribute insights into the thermal enhancement of DPHX and heat pipes using varied molar Ag ornamented GO hybrid nanofluids, further advancing the field.

3. RESEARCH GAP ANALYSIS

The identification of research gaps has been systematically compiled through a thorough review and analysis of relevant literature sources.

- Very limited research has been done on examining how changing the molar concentrations of Ag nanoparticles over GO impacts thermal studies and heat transfer applications.
- There is a scarcity of papers that have explored the thermophysical properties of varied molar Ag-ornamented GO hybrid nanofluids.
- There hasn't been extensive research on how the varying molar concentrations of Ag over GO hybrid nanofluids affect the thermal performance of a double pipe heat exchanger, especially in terms of both experimental and mathematical modeling studies.
- There are not many earlier studies that have focused the thermal performance of heat pipe using varied molar Ag-GO hybrid nanoparticles combination.

4. OBJECTIVE OF THE RESEARCH AND PHASES OF INVESTIGATION

- To synthesize the varied molar Ag ornamented GO hybrid nanoparticles using chemical reduction approach.
- To characterize the hybrid nanoparticles using different techniques to confirm successful synthesis and to prepare the varied molar Ag ornamented hybrid nanofluids through two-step method with good stability results.

- To experimentally determine the thermophysical properties, reactivity, and contact angle measurement of prepared hybrid nanofluids.
- To investigate the thermal performance of double pipe heat exchanger using varied molar Ag-GO hybrid nanofluids experimentally and mathematically.
- To study the thermal performance of heat pipe using varied molar Ag-GO hybrid nanofluids experimentally. The Figure 1 shows the phases of research investigation.

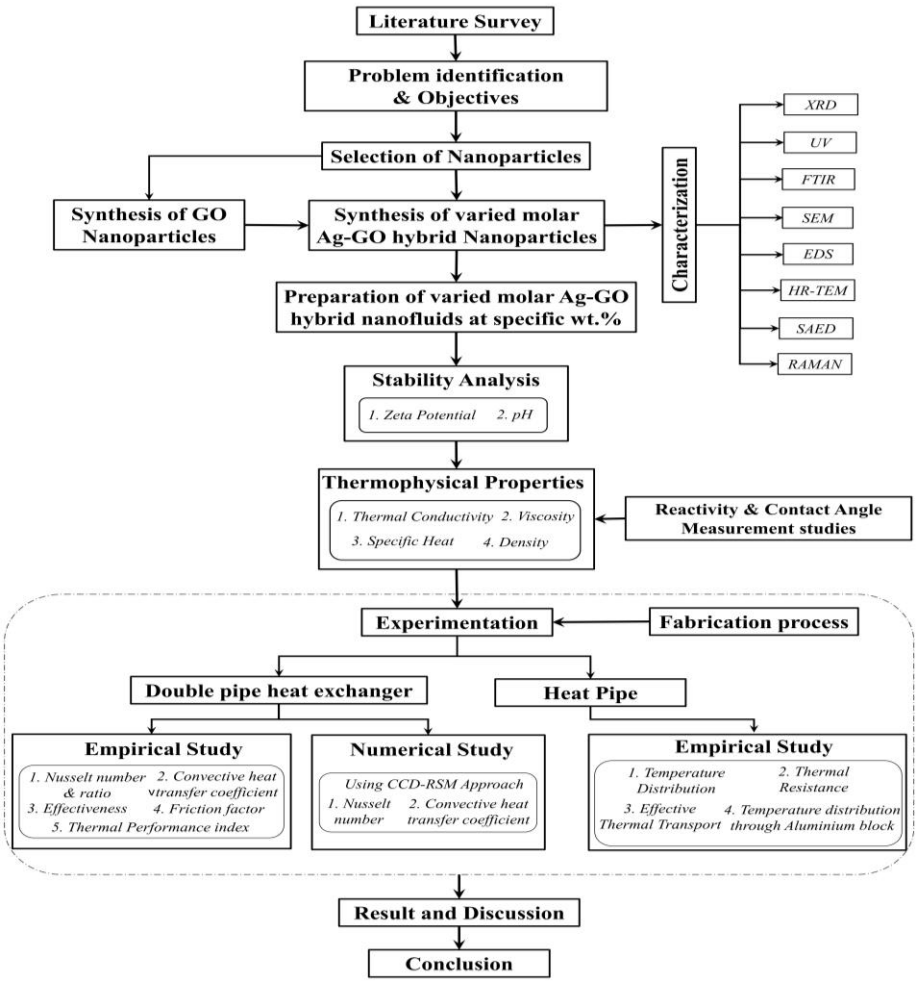

Figure 1 Phases of Research Investigation

5. MATERIALS AND METHODS

5.1 SYNTHESIS OF AG-GO NANOPARTICLES

The GO nanoparticles were synthesised using a modified Hummer's method [13]. The Ag-GO nanohybrids were prepared by combining freshly synthesized GO nanoparticles with varied molar concentrations of Ag metal precursors. First, GO nanosuspensions were ultrasonicated in double distilled water (DW) for 2 hours. Then,

appropriate concentrations of $AgNO_3$ solutions (0.03 M, 0.06 M, and 0.09 M) were blended with Vitamin C (ascorbic acid, 1 ml, 10^{-3} M) as a reducing agent and trisodium citrate (1 ml, 10^{-3} M) as a stabilizing agent. This resulted in a varied Ag-concentrated solution, stirred continuously for 1 hour at room temperature. The reducing and stabilizing agents controlled the size and morphology of Ag nanoparticles. The varied Ag ornamented GO nanostructures were obtained by titrating the prepared Ag solutions uniformly with a definite GO solution. The resulting Ag ornamented GO nano solution was stirred at 90 rpm without adding light or heating during the 48 hours until a fusion of Ag-GO hybrid solution was formed. The solution was then sonicated for 2 hours to ensure better dispersions. The Ag-GO solution was filtered, rinsed with DW and alcohol until the potential of hydrogen (pH) was close to 7.4-7.6, and then treated in a vacuum hot air oven at 50°C to yield 0.03 M, 0.06 M, and 0.09 M Ag ornamented GO hybrid nanoparticles. Figure 2 illustrates the preparation of Ag-GO hybrid nanofluids.

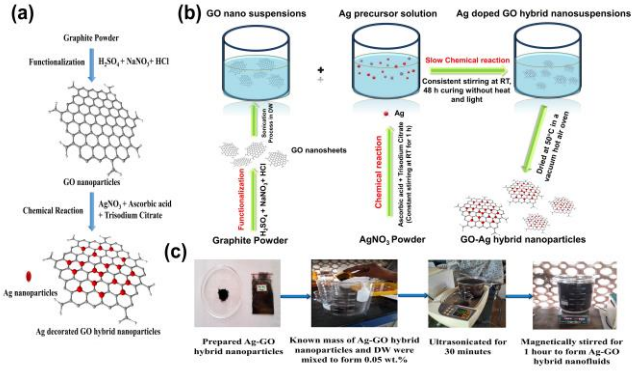

Figure 2 (a) Chemical Structural formation, (b) Schematic representation of the preparation of Ag-GO hybrid nanoparticles, (c) Two step preparation process

In this study, the different molar concentrations (0.03 M, 0.06 M, and 0.09 M) of Ag ornamented GO hybrid nanofluids has been prepared using a two-step process from double distilled water (DW). To achieve optimal dispersion, each synthesized Ag-GO nanohybrids was mixed with a known mass (m_{bf}) of DW, then ultrasonicated for 30 minutes and stirred for 1 hour using a magnetic stirrer. Uniformity was maintained by keeping a constant weight percentage (φ) of 0.05% by controlling the nanoparticle's mass (m_{np}) for all samples using the digital weighing machine of accuracy 0.001g, as estimated using Equation 1.

$$m_{np} = \frac{\varphi \cdot m_{bf}}{1-\varphi} \tag{1}$$

5.2 CHARACTERIZATION TECHNIQUES

The Ag-GO hybrid nanoparticles were characterized using various instruments including Powder X-ray diffraction (XRD-D8 Advance ECO Bruker), UV-visible Spectrometer (SL210, Elico, India), Fourier Transform Infra-Red Spectrophotometer (IR Tracer-100 Shimadzu), High-Resolution Transmission Electron Microscope (HRTEM, JEM-2100 Plus, JEOL Japan, at 200 KV), Scanning Electron Microscope (SEM, EVO 18, CARL ZEISS, Jena, Germany), Energy Dispersive X-Ray Spectrometer (EDAX, Quantax 200 with X-Flash), Laser Raman Spectrometer (STR 500, Seki, Tokyo, Japan), and Particle Size Analyzer (Horiba SZ-100Z). The thermophysical properties of the nanofluids were evaluated using KD2 Pro thermal property analyser (Decagon, USA), LVDVE (Brookfield Engineering Labs, USA), SITA Dynotester (SITA process solution, Germany), Differential Scanning Calorimetry (DSC, SETARAM), and Force Tensio-meter (Bioline scientific, sigma 700).

5.3 CHARACTERIZATION STUDIES OF AG-GO HYBRID NANOPARTICLES

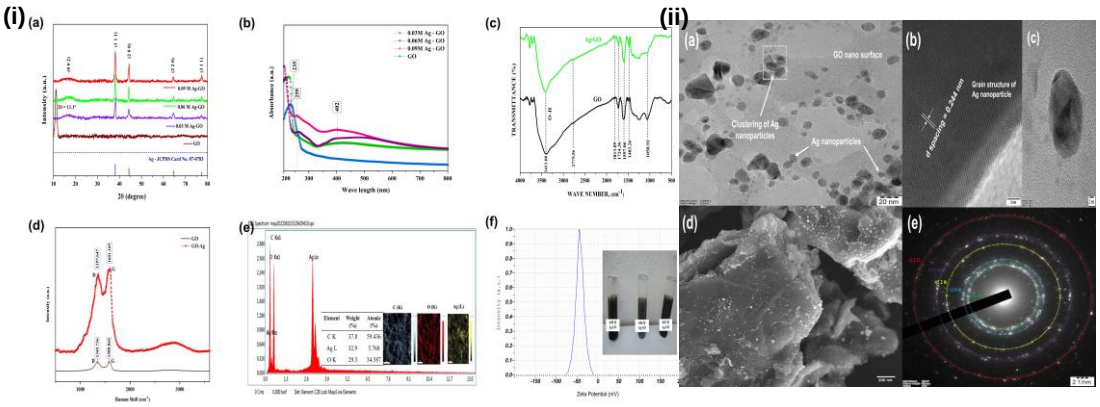

Figure 3 Characterization results (i) (a) XRD, (b) UV, (c) FTIR, (d) Raman, (e) EDS, (f) Zeta Potential Analysis, & (ii) (a) TEM, (b) & (c) HR-TEM, (d) SEM and (e) SAED analysis of 0.09M Ag-GO hybrid nanofluids

The initial XRD analysis confirmed the successful formation of hybrid structures by depositing varying concentrations of silver (Ag) on the graphene oxide (GO) surface. In Figure 3i(a), the presence of GO was validated by observing peaks at the diffracted Bragg angle $2\theta = 11.1°$ in the GO graph. However, in the Ag-GO graph, the GO peak at 11.1° disappeared, and a new expanded broad peak emerged at 16.94° (0 0 2), indicating successful embedding of Ag nanoparticles onto the GO surface [14]. Similarly, the presence of Ag nanoparticles was shown by the various peaks at 38.1° (111), 44.3° (200), 64.5° (220), and 77.3° (311), confirming a face-centered cubic (fcc) crystal lattice with a

cubic structure (JCPDS Card no. 07-0783 [12]). The sharp peak at 38.1° confirmed the presence of pure crystalline Ag nanoparticles, with increasing peak intensity as Ag concentration increased from 0.03M to 0.09M in the Ag-GO hybrid nanoparticles.

The UV analysis complemented the XRD results and showed the successful synthesis of Ag-GO hybrid nanoparticles at different molar concentrations. In Figure 3i(b), the absorption peak at 235 nm on the GO graph indicated the presence of GO nanoparticles. However, on the Ag-GO graph, a shift in the GO absorption peak from 235 nm to 259 nm was observed. This shift happened due to certain electronic transitions ($\pi \rightarrow \pi^*$ and $n\text{-}\pi^*$) in sp^2 poly-aromatic carbon structures and the partial reduction of the GO surface caused by the deposition of Ag nanoparticles during the synthesis process [14]. Additionally, different broad peaks at 402 nm on the Ag-GO graph showed the existence of Ag nanoparticles with varying concentrations on GO nanosheets' surfaces. This confirmed the diverse compositions of Ag over GO hybrid nanoparticles created during synthesis [14].

In the Ag-GO FTIR graph (Figure 3i(c)), reductions in O-H bending vibrations (3412.08 cm^{-1} and 1058.92 cm^{-1}) and reverse changes in carbonyl stretching vibrations (1724.6 cm^{-1} and 1597.06 cm^{-1}) suggest an interaction between Ag nanoparticles and GO nanosheets' oxygenated functional groups, potentially forming consistent electrostatic attractions or chemical bonds [14]. Figure 3i(d) shows the Raman scattering results, indicating energy bands in GO: G (1580.865 cm^{-1}) and D (1345.736 cm^{-1}), associated with carbon-carbon bond stretching. In Ag-GO hybrid nanoparticles, shifts were observed: D band shifted to 1357.647 cm^{-1} and G band shifted to 1601.169 cm^{-1} [15]. This shifts and lengthening of Ag-GO spectral bands suggests Ag association over GO and surface-enhanced Raman scattering platform formation [15]

Figure 3i(e) showcases the Energy Dispersive Spectrum (EDS) analysis conducted on SEM, providing confirmation of the elemental composition in the 0.09M Ag-GO hybrid sample. The analysis revealed the presence of Carbon (K shell), Oxygen (K shell), and Ag (M and L shell) with weight percentages of 37.8%, 29.3%, and 32.9%, respectively. These results serve as robust evidence supporting the existence of both Ag and GO elements in the hybrid samples. The measurement, known as the Zeta potential or electro-kinetic potential, plays a critical role in governing the particle's aggregation or flocculation within the fluid. The higher the surface charge, the more stable the nanofluid

[16]. As shown in Figure 3i(f), the mean Zeta potential value of the 0.09 M Ag-GO hybrid nanofluid was -43.6 mV, indicating that the nanoparticles have a large negative surface charge near the edge of the diffuse layer, thereby demonstrating excellent stability. This stability was achieved by maintaining a pH value of 7.4 -7.6 during the preparation of all nanofluids. These studies helped to understand the significant stability span of approximately 25 days with no nanoparticle aggregation.

Figure 3ii (a-e) presents the TEM, HRTEM, SEM and SAED analyses of 0.09M Ag-GO, revealing the morphology and crystallinity of the Ag nanoparticles over GO. The obtained TEM and SEM images showcased an amorphous, flaky structure of GO nanostructures interwoven with quasi-cubical Ag nanoparticles [17]. Delving deeper into the morphology, Figure 3ii (a) and (d) unveiled the existence of Ag nanoparticles with diverse sizes, ranging ~3-35 nm, often aggregating into clusters. Subsequently, through HR-TEM and SAED analyses in Figure 3ii (b, c & e) revealed a polycrystalline grain structure with an fcc lattice. This lattice was consistent with the d-spacing of 0.244 nm for Ag nanoparticles, and the h k l plane indices were found to be in agreement with the XRD results.

6. EXPERIMENTAL SETUP AND PROCEDURES

6.1 DOUBLE PIPE HEAT EXCHANGER EXPERIMENTAL PROCEDURE

The experimental setup consists of an inner copper pipe for the hot fluid side and an outer Chlorinated polyvinyl chloride (CPVC) annulus pipe for the cold fluid side. The cold fluid flow rate ranges from 8 to 47 g/s to achieve a laminar flow regime (Reynolds number 250 - 1451) with a constant inlet temperature of 35℃, while the hot fluid side has a constant input temperature of 55℃ and a flow rate of 17 g/s. The measurements are averaged from five sets of readings taken under equilibrium conditions with a 30-minute hold time for each set. The study focuses on evaluating the convective heat transfer coefficient, Nusselt number, thermal performance index, friction factor, and effectiveness of the double pipe heat exchanger (DPHX) using different concentrations (0.03M, 0.06M, 0.09M) of Ag-GO hybrid nanofluid with a consistent weight percentage of 0.05 wt.%.

6.1.1 Uncertainty Assessment of DPHX

To ensure data reliability, Moffat's technique [18] was used to estimate uncertainty, analysing recorded results with partial differential equations. The uncertainties for heat

transfer rate (Q), convective heat transfer coefficient (h), Reynolds number (Re), Nusselt number (Nu), and friction factor (f) were calculated as ±4.160%, ±5.433%, ±1.303%, ±5.610%, and ±4.127%, respectively. These uncertainty levels reflect the ability to reproduce experimental results within reported error margins.

6.2 HEAT PIPE EXPERIMENTAL PROCEDURE

The different heat pipes were used with DW and varying molar concentrations (0.03M, 0.06M, and 0.09M) of Ag-doped GO hybrid nanofluids as working fluids. The copper heat pipes consisted of evaporator, adiabatic, and condenser sections each measuring 100 mm, with insulation in the evaporator section using glass wool, wooden shell, and cotton threads. The condenser section had an annulus pipe for cold fluid flow, regulated by a rotameter. The exit fluid was cooled through a double pipe heat exchanger using distilled water as the cooling fluid, with submersible pumps transporting cold fluid from the tank to the condenser section and outlet fluid from the collecting tank to the heat exchanger. Figure 4 depicts the schematic and pictorial representation of the DPHX and HP experimental setups.

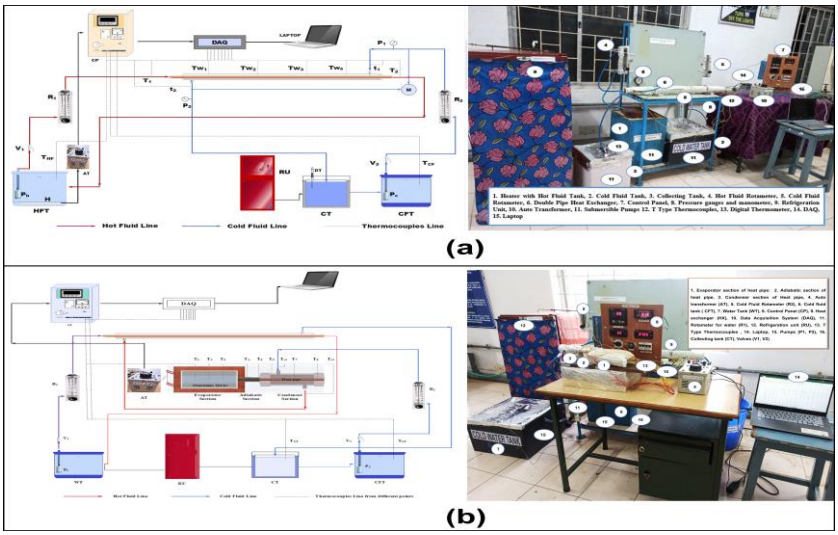

Figure 4 Schematic and Pictorial representation of (a) DPHX, (b) HP

6.2.1 Uncertainty Assessment of heat pipe

The uncertainties of the heat load and thermal resistance were resulting in the uncertainty values of ±0.306% and ±0.527%, respectively.

7. RESULTS AND DISCUSSION

7.1 THERMOPHYSICAL PROPERTIES

7.1.1 Thermal Conductivity

The thermal conductivity (K) of the base liquid (DW) was initially measured and compared to standard data from Incorpera, Dewitt, Bergman, Lavine [19]. The results demonstrated the predictive relevance of the evaluated and standard data, with uncertainties calculated using average values of measurements with >0.99 correlation coefficient. Thermal conductivity exhibited a consistent increase with rising temperature and molar concentration of Ag in GO. Notably, at 293 K, improvements of 8.03%, 11.04%, and 13.71% were observed for 0.03M, 0.06M, and 0.09M Ag-GO, respectively, compared to the base fluid. Enhancements were even more significant at 333 K, reaching approximately 17.13%, 22.63%, and 30.12% for respective concentrations. These enhancements were attributed to mechanisms like Brownian motion, electron-phonon collision, lattice vibration due to percolation effect, and enhanced surface area due to Ag nanoparticles clustering on GO [13].

7.1.2 Viscosity

The viscosity of the nanofluids increased with higher concentrations of Ag nanoparticles in GO, especially at lower temperatures. This suggests the need for an optimal concentration for effective thermal improvement at specific temperature rises. For example, at 293 K, the 0.09M Ag-GO hybrid nanofluid had higher viscosity (0.00114 Pa.s) compared to other concentrations and the base fluid. As temperature increased, viscosity values for all concentrations decreased. At 333 K, the viscosity (0.00053 Pa.s) of the 0.09M Ag-GO concentration approached similar levels to other concentrations and the base fluid.

7.1.3 Surface Tension

At 293 K, the 0.09M Ag-GO hybrid nanofluid had higher surface tension than other molar concentrations. As temperature increased, the values of surface tension for all concentrations decreased. At 333 K, the 0.09M Ag-GO concentration approached a similar value of surface tension (72.7 mN/m) to other concentrations and the base fluid. Surface tension influences surface wettability and bubble growth during temperature changes, affecting heat transfer in nanofluids [16]. The reduction in surface tension contributes to improved heat transfer in the nanofluids [20].

7.1.4 Density and specific heat

The density of the varied Ag-GO hybrid nanofluids did not impact much due to the negligible change in the mass of the hybrid nanoparticles. The specific heat capacity of the nanoparticles decreased with increasing concentration and increased with temperature [21]. When compared to the base fluid, the specific heat of nanoparticles was lower, and increasing the temperature increases the specific heat with a minor dip at 313K. At low and high temperatures, all concentrated nanoparticles performed better than the base fluid, with 0.09M Ag-GO hybrid nanoparticles having superior thermal properties at higher temperatures.

7.2 THERMAL PERFORMANCE OF AG-GO HYBRID NANOFLUIDS IN DPHX

7.2.1 Influence of Nusselt number

The Nusselt number results for distilled water (DW) were obtained under laminar flow conditions (Re < 2300) and compared with correlations from previous studies. The comparison demonstrates a good match with the correlations, particularly the Hausen equation which had a maximum difference of only ±8%, falling within the acceptable range of ±10%. The Nusselt number of various concentrations of Ag-GO hybrid nanofluids was measured and compared with the Nusselt number of the base fluid at different mass flow rates (8 g/s - 47 g/s) and Reynolds numbers (250 - 1451). The results revealed a significant increase in the Nusselt number with higher Reynolds numbers, mass flow rates, and molar concentrations of Ag-GO hybrid nanofluids. This implies that Reynolds number, molar concentration of Ag-GO hybrid nanofluids, and their enhanced thermophysical properties, especially thermal conductivity, have a notable impact on Nusselt number values [22].

At a Reynolds number of 1451, nanofluids exhibited Nusselt number increments of 33.55%, 27.62%, and 18.35% for Ag concentrations of 0.09M, 0.06M, and 0.03M, respectively, compared to the base fluid. Similarly, at a Reynolds number of 250, the Nusselt number increased by 19.80%, 14.94%, and 9.64% for 0.09M, 0.06M, and 0.03M Ag-GO hybrid nanofluids, respectively, compared to the base fluid.

7.2.2 Convective heat transfer coefficient

The DW and hybrid nanofluids exhibit a gradual increase in the h value with increase in Reynolds numbers (250 to 1451) and mass flow rates (8 to 47 g/s) of the fluids. At Reynolds number 1451, there is a significant enhancement of 62.9%, 50.82%, and 34.34% for 0.09M, 0.06M, and 0.03M Ag-GO hybrid nanofluids, respectively, compared to the base fluid. Conversely, at Reynolds number 250, the h value shows a lower improvement of 45.50% (0.09M), 35.16% (0.06M), and 23.80% (0.03M) compared to the base fluid. The incorporation of high conductive nanoparticles (Ag-GO) in the base fluid leads to higher performance in convective heat transfer coefficient in DPHX. The 0.09M Ag doped GO hybrid nanofluids exhibited superior results compared to other concentrations and base fluids. On the annulus side, heat transfer coefficient increase is more prominent at low Reynolds number. The h value improvement is directly related to Nusselt number, influenced by Reynolds number, thermal conductivity, and Prandtl number.

7.2.3 Friction Factor

The theoretical friction factor was calculated using the Darcy equation, while the experimental factor was determined by measuring annulus pressure drop. The deviation between these factors showed strong agreement, with an average deviation of ±4.1% across Reynolds numbers. The results indicated that experimental and theoretical friction factors decreased similarly as Reynolds number increased. At a low mass flow rate of 8 g/s and Reynolds number of 250, the highest friction factors were observed in 0.09 M, 0.06 M, and 0.03 M Ag-GO at 8.9%, 5.7%, and 3.1%, respectively. This highlights the impact of dispersing minimal nanoparticles in enhancing pressure drop and increasing friction factor values at low Reynolds numbers and mass flow rates.

7.2.4 Thermal Performance Index

The thermal performance index (η) is a key factor for predicting the system's efficiency, where a value above one indicates superior heat transfer with minimum delay [22]. The molar concentration of Ag relative to GO had a significant impact on nanofluid's heat transfer and performance, especially at higher Re and flow rates. Notably, the nanofluid with 0.09 M Ag concentration over GO had the highest 'η' value of 1.29 at Re 1451, outperforming other Ag concentrations. At the same Re, other nanofluids showed 'η' increments of 1.25 (0.06 M Ag-GO) and 1.17 (0.03 M Ag-GO), indicating that even

lower dispersion of Ag over GO can significantly enhance the heat exchanger's performance compared to the base fluid.

7.2.5 Influence of flow rate vs Effectiveness

The effectiveness of the DPHX can be evaluated by comparing the actual heat transfer achieved to the maximum feasible heat transfer. The hybrid nanofluids exhibited a significantly higher increase in effectiveness for all concentrations of Ag over GO compared to the base fluid. Notably, the highest effectiveness was observed at a flow rate of 47 g/s and with concentrations of 0.09 M, 0.06 M, and 0.03 M of Ag over GO hybrid nanofluid, resulting in efficacy values of 35.2%, 31.1%, and 29.4%, respectively.

7.3 NUMERICAL ANALYSIS USING CCD-RSM APPROACH

The Central Composite Design (CCD) is an effective method for analysing the impact of input factors on the output/response variable. A second-order polynomial model within CCD-Response Surface Methodology (RSM) was developed to predict the experimental response variables includes Nusselt number (Nu) and heat transfer coefficient (h). The input variables include Graetz number (Gz), thermal conductivity of fluids (K), and molar concentrations (ξ) of Ag over GO. Graetz number characterizes laminar flow and relates Reynolds number, Prandtl number, and thermally developed flow entrance region.

$$Y = \beta_o + \sum_{i=1}^{n} \beta_i x_i + \sum_{j=1}^{n} \beta_{ii} x_i^2 + \sum_{i=1}^{n-1} \sum_{i}^{n} \beta_{ij} x_i x_j + e \qquad (2)$$

The predicted response factor (Y) in Eq. 2 is determined by regression coefficient ($\beta_{o)}$, linear (β_i), quadratic (β_{ii}), and interaction (β_{ij}) coefficients. The experimental residual errors are represented by 'e', while $'x_i'$ and 'x_j ' denote process variables. The evaluation graph and correlation scatter plot visually assess the precision of the design model, showing correlation points of 0.918 and 0.813 for Nu and h responses. The results of contour plots and 3D surface plots illustrate the impact of increasing molar concentration on thermal conductivity and Gz number, resulting in enhancements in Nu and h values, with the most significant enhancement at 0.09M molar concentration. The actual and predicted response values demonstrate the high precision of the mathematical analysis calculated from the ANOVA table and it forms the second order polynomial equation for the predicted model of the experimental results (Nu and h). The normal probability plots of residuals exhibit a linear pattern without significant scatter, indicating

a formation of better analysis. Numerical optimization with assigned desirability functions meets optimization goals. The percentage of deviation for predicted and experimental results at optimal points is ±0.20 and ±0.17, indicating a favourable agreement between predicted and experimental outcomes.

7.4 THERMAL PERFORMANCE OF HEAT PIPE

7.4.1 The Impact of Wall Temperature Variation

In the evaporator section of the heat pipe, the wall temperature distribution was observed at a 100W heat load, resulting in dry out with DW as the working fluid. The temperature variation data were mapped at the optimal heat load of 100W for comparison between DW and hybrid nanofluids. Wall temperatures were measured using DW and different molar concentrations (0.03M, 0.06M, 0.09M) of Ag-GO nanofluids at mass flow rates of 8 g/s, 16.66 g/s, and 25 g/s. The high thermal conductivity of hybrid nanoparticles reduced wall temperatures, with maximum reductions in the evaporator section of 27.52%, 17.32%, and 9.34% for 0.09M, 0.06M, and 0.03M Ag-GO nanofluids at a mass flow rate of 16.66 g/s. Similar reductions were observed at the 25 g/s mass flow rate, with temperature reductions of 24.40%, 15.34%, and 7.30% for 0.09M, 0.06M, and 0.03M Ag-GO hybrid nanofluids. This confirms that the 16.66 g/s mass flow rate outperforms the 25 g/s mass flow rate, i.e., the increase in the mass flow rate after 16.66 g/s might leads to drop in the performance of the heat pipes. The presence of hybrid nanoparticles also enhanced the thermal performance of the heat pipes, through improved surface contact and larger porosity surface area.

7.4.2 Thermal Resistance in heat pipe

Thermal resistance (R_{HP}) indicates heat transfer efficiency in the heat pipe. As heat load increases, thermal resistance decreases rapidly, improving heat transfer. Reduction in thermal resistance levels off at dry out condition. Using 0.09M Ag-GO nanofluid, thermal resistance decreases by 50.48%. For 0.06M and 0.03M Ag-GO nanofluids, reductions are 32.35% and 20.36% at 16.66 g/s flow rate. The flow rate of 16.66 g/s outperforms 25 g/s and 8.33 g/s rates, with percentage increases of 15.04% and 28.98% using 0.09M Ag-GO nanofluids. At heat load of 10W to 100W with 0.09M Ag-GO nanofluid, temperature reductions are 76.8%, 91.78%, and 82.46% at 8.33 g/s, 16.66 g/s, and 25 g/s flow rates.

7.4.3 Effective Thermal Transport

The results illustrate the relationship between varying concentrations (0.03M, 0.06M, and 0.09M) of Ag-GO hybrid nanofluids and mass flow rates of the cooling fluid on the heat pipe's effective thermal transport (K_{eff}) at a constant heat load of 100W. Notably, at a concentration of 0.09M Ag-GO hybrid nanofluids and a mass flow rate of 16.66 g/s, there is a significant enhancement of approximately 32.66 kW/m. ℃ in K_{eff}, indicating improved heat transfer performance.

7.4.4 Temperature Distribution in Aluminium Block

The investigation examined surface temperature distribution of aluminium block with and without heat pipes, using different working fluids and cooling fluid at a mass flow rate of 16.66 g/s. Results showed significant temperature increase without heat pipes, reaching 90.3°C in 2100 seconds at steady state with an ambient temperature of 30℃. Heat pipes reduced temperature rise due to high thermal conductivity and heat removal rate. Surface temperature reached 84.2°C with DW in the heat pipe, and even lower temperatures were achieved with Ag-GO hybrid nanofluids: 75.7°C, 68.9°C, and 60.3°C for concentrations of 0.03M, 0.06M, and 0.09M respectively. Heat pipes improved heat transfer rate, maintained optimal working temperatures, and minimized the risk of overheating in aluminium blocks. Applications include plastic injection moulding, die casting, and battery heat recovery systems. In plastic injection moulding, it could ensure precise thermal regulation and efficient cooling to prevent defects like sink marks and warpage. Heat pipes offer benefits like reduced cycle time, costs, and improved temperature distribution.

7.5 REACTIVITY AND CONTACT ANGLE STUDIES

The concept of surface wettability, which determines how effectively a liquid spread on a solid surface, is crucial in heat transfer applications [16]. Contact angle measurements were conducted on smooth and rough copper substrates at room temperature to understand this phenomenon for double distilled water (DW) and a 0.09M Ag-GO hybrid nanofluid. The results showed that both DW (92.83°) and nanofluid (94.30°) exhibited hydrophobic (>90°) behaviours on smooth copper surfaces, characterized by larger contact angles. However, on rough copper substrates, the nanofluid demonstrated a hydrophilic nature with lower contact angles (79.90°) compared

to DW (84.93°), indicating higher surface wettability. This suggests that the 0.09M Ag-GO hybrid nanofluid possesses superior wetting ability on rough surfaces, potentially leading to enhanced convective heat transfer coefficient.

A reactivity investigation was conducted on a rough copper surface immersed in the hybrid nanofluids, and the results revealed that the Ag-GO nanoparticles underwent a reduction chemical reaction and effectively coated the copper surface, confirmed through SEM and EDS results. These observations confirm the potential of hybrid nanoparticles coating in enhancing the performance of heat exchanging systems.

7.6 KEY FINDINGS OF THE RESEARCH

- The successful synthesis and preparation of the varied molar Ag ornamented GO hybrid nanofluids has been conducted and the characterization techniques including HR-TEM, XRD, UV visible spectrometer, FTIR, SEM, EDS, and Raman scattering were employed and revealed the enhanced surface chemistry and binding of Ag-GO nanoparticles.
- The Ag-GO hybrid nanofluids exhibited stability for up to 25 days, with higher zetapotential value observed at 0.09M Ag-GO hybrid nanofluid.
- Thermophysical properties such as thermal conductivity, viscosity, density, surface tension, and specific heat were investigated. The 0.09M Ag-GO hybrid nanofluid demonstrated a significant enhancement in thermal conductivity of approximately 30.12% at 333K.
- Newtonian behaviour of nanofluids leads to the viscosity and surface tension reduction with increased temperatures. Overall, this study enhances understanding of optimum molar Ag doping on GO hybrid nanofluids for potential applications in thermal management and heat transfer processes.
- The experimental analysis of DPHX using Ag-GO hybrid nanofluids showed a significant improvement in convective heat transfer coefficient (62.9%) and Nusselt number (33.55%) is observed with 0.09M Ag-GO nanofluid at Reynolds number 1451 and flow rate of 47 g/s.
- The overall effectiveness and thermal performance index reached 35.2% and 1.29 respectively for 0.09M Ag-GO nanofluid.
- Furthermore, a mathematical modelling using the CCD-RSM approach successfully developed a mathematical model that aligned well with experimental results, illustrating the influence of input factors on the response factors through

graphical analysis and ANOVA. The study's outcomes indicated a favourable agreement between the predicted and experimental results, confirming the accuracy of the CCD-RSM model's predictions.

- The study's results show promise in understanding how heat inputs, working fluids, and mass flow rates impact heat pipe's performance. The increasing Ag concentration on GO improved heat pipe efficiency.
- Using 0.09M, 0.06M, and 0.03M Ag-GO nanofluids reduced wall temperatures in the evaporator section by 27.52%, 17.32%, and 9.34%, respectively, at 16.66 g/s flow rate. Thermal resistance decreased by 50.48% with 0.09M Ag-GO at 100W heat input.
- The most efficient flow rate, 16.66 g/s, yielded enhanced temperature distribution in the aluminium block compared to the base fluid.
- Reactivity study and contact angle studies of hybrid nanoparticles showed improved copper surface chemistry and contact angle respectively, confirming enhanced DPHX and heat pipe performance.
- In conclusion, optimal molar concentrated Ag-GO nanofluids show potential in heat exchanging systems applications includes plastic injection molding, batteries of car, bikes etc., condensing systems in refrigerators, and mechanical machines.

7.7 ORGANIZATION OF THESIS

The organization of the thesis is structured to provide a comprehensive understanding of the research study.

Chapter 1 discusses a detailed overview of heat exchanging systems, their classifications, and various applications. Additionally, the concept of nanofluids is introduced, discussing their classifications, methods of preparation, and their significance in enhancing the efficiency of heat exchange processes.

Chapter 2 focuses on the literature survey, serves as a building block for the study, offering insights from previous research studies, methodologies, and findings. The survey covers various aspects such as the preparation, thermophysical properties, and the experimental and mathematical studies on the enhancement of heat exchangers and heat pipes using nanofluids. The identification of research gaps and formulation of research

objectives are derived from the literature review, leading to the development of proposed research methodologies.

Chapter 3 discusses the synthesis and characterization studies of different molar Ag-GO hybrid nanoparticles. It also covers the preparation of hybrid nanofluids and analyzes the stability of these nanofluids using zeta potential and pH measurements.

Chapter 4 explains the design and fabrication of experimental setups for double pipe heat exchangers and heat pipes, providing schematic illustrations, experimental procedures, data reduction, and uncertainty assessments.

Chapter 5 describes the findings related to thermophysical properties, as well as the thermal performance measurements of DPHX and heat pipes using Ag-GO hybrid nanofluids. Numerical study using CCD-RSM framework in DPHX and the reactivity analysis and the contact angle measurements of Ag-GO hybrid nanofluids on copper substrate are discussed.

Chapter 6 concludes the thesis with a summary of the findings and implications, along with suggestions for future research directions.

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LIST OF PUBLICATIONS

1. **M. Armstrong**, M. Sivasubramanian, N. Selvapalam, Carlo Santulli, P. Sivasubramanian and Cristiano Fragassa. Augmenting the double pipe heat exchanger efficiency using varied molar Ag ornamented graphene oxide (GO) nanoparticles aqueous hybrid nanofluids, *Frontiers in Materials*, **10**, (2023), 1240606.
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